

f

NASA TECHNICAL NOTE



NASA TN D-2975

NASA TN D-2975

AMPTIAC

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited



OPTIMIZATION OF TIME-TEMPERATURE
PARAMETERS FOR CREEP AND
STRESS RUPTURE, WITH APPLICATION
TO DATA FROM GERMAN COOPERATIVE
LONG-TIME CREEP PROGRAM

Reproduced From
Best Available Copy

*by Alexander Mendelson, Ernest Roberts, Jr.,
and S. S. Manson*

*Lewis Research Center
Cleveland, Ohio*

20011210 132

OPTIMIZATION OF TIME-TEMPERATURE PARAMETERS FOR CREEP
AND STRESS RUPTURE, WITH APPLICATION TO DATA FROM
GERMAN COOPERATIVE LONG-TIME CREEP PROGRAM

By Alexander Mendelson, Ernest Roberts, Jr.,
and S. S. Manson

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - Price \$2.00

OPTIMIZATION OF TIME-TEMPERATURE PARAMETERS FOR CREEP AND STRESS RUPTURE, WITH
APPLICATION TO DATA FROM GERMAN COOPERATIVE LONG-TIME CREEP PROGRAM

by Alexander Mendelson, Ernest Roberts, Jr., and S. S. Manson

Lewis Research Center

SUMMARY

By the use of orthogonal polynomials developed for discrete sets of data, the least-squares equations for determining the optimized stress-rupture parametric constants are obtained in nearly uncoupled form; thus the use of high-degree polynomials is permitted without the loss of significant figures. Optimum values of the constants can thereby be accurately obtained. The method is applied to the data obtained from the German cooperative long-time creep program by using a general parameter of which the Manson-Haferd and Larson-Miller parameters are special cases. Good correlation was obtained. An analysis is also made of creep data obtained for columbium alloy FS-85 with good results. A complete Fortran IV computer program is included to aid those wishing to use the method.

INTRODUCTION

One method of extrapolating short-time creep-rupture data to predict long-time life involves the use of a time-temperature parameter. This concept is based on the assumption that all creep-rupture data for a given material can be correlated to produce a single "master curve" wherein the stress (or log stress) is plotted against a parameter involving a combination of time and temperature. Extrapolation to long times can then be obtained from this master curve, which can presumably be constructed by using only short-time data. Three well-known parametric methods are the Larson-Miller, Manson-Haferd, and Dorn parameters (refs. 1 to 3). These parametric methods have the great advantage, at least in theory, of requiring only a relatively small amount of data to establish the required master curve.

More recently a general creep-rupture parameter was introduced by one of the authors (ref. 4) that includes most of the currently used parameters as special cases. The analysis in the present paper is therefore based on this general parameter.

A significant advance in the practical application of the parametric methods was the development of an objective least-squares method for determining the optimum values of the parametric constants without plotting and cross-plotting the data and without the use of judgment on the part of the analyst (ref. 5). This least-squares method involves, however, several practical difficulties that arise from the fact that in fitting the master curve by a polynomial, the set of linear algebraic equations for the coefficients (the normal equations) are very ill-conditioned. The determinant of these equations can be shown to be related to the Hilbert determinant (ref. 6), which rapidly approaches zero as its order increases. Thus for polynomials above the second degree, it is necessary to use double-precision arithmetic (16 significant digits or more) on the computer, and for the fifth degree and above the results become uncertain even with double-precision arithmetic. This difficulty is inherent in the normal least-squares equations and is not limited only to the stress-rupture problem.

The present report presents a method for avoiding the above difficulty by using orthogonal polynomials in the representation of the master curve (appendix A). The use of orthogonal polynomials for representing discrete sets of unequally spaced data is described in reference 6 and in more detail in reference 7. A further improvement can be obtained by performing a linear transformation on the stresses (or the logs of the stresses) so that all the values of stress (or log stress) lie between 2 and -2, as recommended in reference 7. As a result of these innovations, it became possible to perform all the computations in single-precision arithmetic (eight significant digits) up to 18th degree polynomials without appreciable round-off error.

In addition, this report contains a complete analysis, in which the general parameter was used, of all the data for three steels that were obtained by NASA through the cooperation of Dr. K. Richard of Faberwerke Hoechst in Frankfurt and that were investigated in a long-time cooperative creep program in Germany. Some of the data from the latter investigation are included in this paper.

Finally it is shown by means of a concrete example how the parameter techniques can be applied to creep data to predict long-time creep. For this purpose the data for columbium alloy FS-85, as reported in reference 8, are used.

A complete Fortran IV program, as used on the IBM 7094 computer in making the calculations, is presented in appendix B. This program can be used for the objective analysis of any set of creep-rupture data by the Larson-Miller, Manson-Haferd, or the more general parameter of reference 4.

SYMBOLS

A,B	linear transformation coefficients
a,b,c	elements of coefficient matrix
D	standard deviation

K	degree of freedom
m	degree of polynomial
n	number of data points
$P(\sigma)$	creep-rupture parameter
Q	polynomial
q	stress exponent
r	temperature exponent
S	sum of squares of residuals
T	temperature
T_a	temperature intercept
t	time to rupture
t_a	time intercept
u	coefficient of polynomial function
X	scaled log stress
x	log stress
y	log time
y_a	log time intercept
α, β	constants from recurrence relation
σ	stress
τ	$\sigma^q(T - T_a)^r$

Subscripts:

max	maximum
min	minimum

PROCEDURE

General Parameter

The general creep-rupture parameter introduced in reference 4 has the fol-

lowing form

$$P(\sigma) = \frac{\frac{\log t}{\sigma^q} - \log t_a}{(T - T_a)^r} \quad (1)$$

where T_a , $\log t_a$, q , and r are material constants to be determined from the available experimental data. The parameter $P(\sigma)$ is a function of the stress and, when plotted against stress, is referred to as a master curve (fig. 1, p. 9). If $q = 0$ and $r = 1$, the Manson-Haferd parameter is obtained. If $q = 0$, $r = -1$, and $T_a = -460^\circ \text{ F}$, the Larson-Miller parameter results. If $q = 1$ and $r = 1$, the stress-modified parameter suggested in reference 9 is obtained. Finally, if $q = 0$, equation (1) reduces to the parameter proposed by Manson and Brown (ref. 10).

The object is to find the best values of the constants q , $\log t_a$, T_a , and r so that the master curve best fits the data. To find these values, the method of least squares is used whereby the master curve is represented by a polynomial in the logarithm of the stress, and the best fit is obtained by minimizing the sum of the squares of the deviations (the residuals) of the data from the curve. The calculation procedure will now be described. The details of the derivation are given in appendix A, and a Fortran IV computer program using this method is given in appendix B.

Calculation Procedure

To simplify the notation, the following symbols are introduced:

$$\left. \begin{aligned} \tau &\equiv \sigma^q (T - T_a)^r \\ y &\equiv \log t \\ x &\equiv \log \sigma \\ y_a &\equiv \log t_a \end{aligned} \right\} \quad (2)$$

Then from equation (1) it follows that

$$y = \sigma^q y_a + \tau Q(x) \quad (3)$$

where in reference 5, $Q(x)$ was represented by a simple polynomial of the form

$$Q(x) = a_0 + a_1 x + a_2 x^2 + \dots + a_m x^m \quad (4)$$

The least-squares equations obtained sometimes led to difficulties as indicated in the INTRODUCTION. These difficulties can be avoided, however, by rewriting equation (4) in terms of polynomials that are orthogonal over the set of data, as defined in appendix A. Thus assume

$$Q(x) = u_1 Q_1(x) + u_2 Q_2(x) + \dots + u_{m+1} Q_{m+1}(x) = \sum_{j=1}^{m+1} u_j Q_j(x) \quad (5)$$

where u_j is an unknown constant, m is the degree of the highest degree polynomial, and $Q_j(x)$ is a polynomial of degree $j - 1$ that satisfies the orthogonality conditions described in appendix A. The use of orthogonal polynomials permits the solution of the least-squares equations directly in closed form, thus the loss of a large number of significant digits is avoided. The method of calculating Q_j will be discussed in appendix A.

If equation (5) is substituted into equation (3), an equation with $m + 5$ unknown constants results for the case of the general parameter. For the case of the linear parameter there are $m + 3$ constants, and for the Larson-Miller parameter there are $m + 2$. It is necessary that the number of data points n always equals or exceeds the number of unknown constants.

The constants are determined so that equation (3) fits the data best in the least-squares sense. To accomplish this, the sum of the squares of the deviations is minimized; that is,

$$S \equiv \sum_{i=1}^n [y_i - \sigma_i^q y_a - \tau_i Q(x_i)]^2 \quad (6)$$

is made a minimum. Because the equations are nonlinear in some of the unknown constants a trial and error procedure must be used. A set of values is assumed for q , r , and T_a , and the corresponding best values of y_a and u_j are determined. A different set of values for q , r , and T_a is then chosen, and again the best values of y_a and u_j are calculated. Several sets of values of q , r , and T_a are tried, and the values corresponding to the overall best fit are determined. For the case of the linear parameter, only the value of T_a is varied (q is always equal to zero, and r is always equal to 1). For the Larson-Miller parameter, T_a is equal to -460°F , and no trial and error procedure is needed.

As a measure of the fit, the standard deviation D , defined by

$$D = \sqrt{\frac{S}{n - K}} \quad (7)$$

is used, where K equals

$m + 5$	general parameter	}	(8)
$m + 3$	linear parameter		
$m + 2$	Larson-Miller parameter		

The smallest value of D will correspond to the best fit.

To determine the best values of y_a and u_j for a given set of values of T_a , q , and r , the following calculations are made. First, the logarithms of the stresses are scaled so that they lie in the range -2 to 2, as suggested in reference 7. The reason for this is discussed in appendix A. Thus define a variable X by

$$X = Ax + B \quad (9a)$$

$$\left. \begin{aligned} A &= \frac{4}{x_{\max} - x_{\min}} \\ B &= -2 \frac{x_{\max} + x_{\min}}{x_{\max} - x_{\min}} \end{aligned} \right\} \quad (9b)$$

The polynomials $Q_j(X_i)$ are now calculated for each of the data points by using the following formulas:

$$Q_{j+1} = (X - \alpha_j)Q_j - \beta_j Q_{j-1} \quad m \geq j \geq 1 \quad (10)$$

$$\left. \begin{aligned} \alpha_j &= \frac{\sum_{i=1}^n X_i \tau_i^2 Q_j^2(X_i)}{\sum_{i=1}^n \tau_i^2 Q_j^2(X_i)} \quad m \geq j \geq 1 \\ \beta_j &= \frac{\sum_{i=1}^n X_i \tau_i^2 Q_j(X_i) Q_{j-1}(X_i)}{\sum_{i=1}^n \tau_i^2 Q_{j-1}^2(X_i)} \quad m \geq j > 1, Q_1 = 1, \text{ and } \beta_1 = 0 \end{aligned} \right\} \quad (10a)$$

where n is the number of data points, X_i is the scaled value of log for the i^{th} data point, and τ_i is equal to $\sigma_i^q (T_i - T_a)^r$ for the i^{th} data point for the chosen values of T_a , q , and r .

It is to be noted that the degree of the polynomial $Q(x)$ of equation (5) can be increased by merely computing the next polynomial in the series Q_{m+2} without having to recompute any of the previous ones. This is one of the advantages of using orthogonal polynomials.

Once the values of Q_j have been computed for each of the data points, y_a and u_j can be calculated as follows:

Let

$$\left. \begin{aligned}
 a_0 &= \sum_{i=1}^n \sigma_i^{2q} \\
 a_j &= \sum_{i=1}^n \sigma_i^q \tau_i Q_j(X_i) \\
 b_j &= \sum_{i=1}^n \tau_i^2 Q_j^2(X_i) \\
 c_0 &= \sum_{i=1}^n \sigma_i^q y_i \\
 c_j &= \sum_{i=1}^n \tau_i y_i Q_j(X_i)
 \end{aligned} \right\} \quad (11)$$

where $j = 1, 2, \dots, m+1$.

Then

$$\left. \begin{aligned}
 y_a &= \frac{c_0 - \sum_{j=1}^{m+1} \frac{a_j c_j}{b_j}}{a_0 - \sum_{j=1}^{m+1} \frac{a_j^2}{b_j}} \\
 u_j &= \frac{c_j - a_j y_a}{b_j}
 \end{aligned} \right\} \quad (12)$$

Note that if $q = 0$, a_0 equals the number of data points n . Thus by means of equations (9) to (12), the best values of y_a and u_j to fit the data are found for a given choice of T_a , q , and r . The Fortran IV program described in appendix B automatically scans all the desired values of T_a , q , and r and chooses the best set from all the submitted values as determined by the smallest value of the standard deviation D , as defined by equation (7). The method can be illustrated by a simple example: consider a set of theoretical data, which fit the following equation exactly

$$\frac{9.5 - \log t}{T - 600} = 10^{-3}(7.02 + 0.467 x + 0.061 x^2 + 0.00928 x^3) \quad (13)$$

Eight data points satisfying this equation are given in columns 2 to 6 of table I. For this data $T_a = 600^\circ \text{ F}$ and $\log t_a = y_a = 9.5$. Suppose, however, that these eight data points were obtained experimentally and that the values of T_a and $\log t_a$ were not known. The problem then is to find the best values of T_a and $\log t_a$ to fit the data by the linear parameter. These values can readily be found by using the equations of the previous section. First, from column 6 of table I

$$(\log \sigma)_{\max} = 4.75051$$

$$(\log \sigma)_{\min} = 1.81954$$

Therefore from equations (9b)

$$A = 1.36474$$

$$B = -4.48319$$

and by means of equation (9a) the X_i were computed and are given in column 8.

For illustrative purposes three values of T_a were chosen, 500° , 600° , and 700° F . For each of these values of T_a , values of T_i , α_j , β_j , and $Q_j(X_i)$ were computed by means of equations (2), (10), and (10a), and the values of a_j , b_j , and c_j were computed by equations (11). The results are tabulated for $T_a = 600^\circ$ in columns 9 to 12 of table I and in table II up to a third degree polynomial.

The values of y_a and u_j were then computed by using equations (12) for each of these three values of T_a by first assuming $m = 2$, then $m = 3$, and finally $m = 4$, corresponding to polynomials of second, third, and fourth degrees, respectively. For each of these cases the standard deviation D was computed from equation (7) with S being given by equation (6) and Q by equation (5). The results are summarized in table III. The least value of D , signifying the best fit, is obtained for $m = 3$ and $T_a = 600^\circ \text{ F}$. The corresponding value of y_a is 9.5. These values, of course, correspond to equation (13), from which the data were generated.

Application to Data from German Cooperative Long-Time Creep Program

As part of the German cooperative long-time creep program, a sufficient amount of material of each of three steels was supplied to NASA to permit the running of short-time tests necessary to predict the results at long times obtained in the German test program. The composition of these steels is shown in table IV.

The results of the NASA tests, which were used in the subsequent analysis,

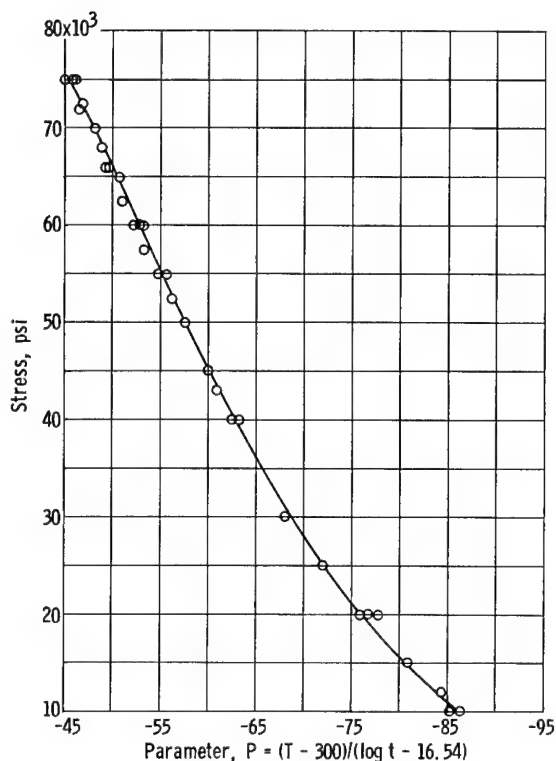


Figure 1. - Master curve for steel K (27b KK), calculated from NASA data between 10 and 3700 hours.

are shown in table V. Table VI shows the results of the long-time German test program. The three steels will be designated briefly as steel K, steel C, and steel P.

With the use of the test data shown in table V a complete analysis was made by the previously described method. The general parameter discussed in the INTRODUCTION was used, and the best values were obtained for the parametric constants for each of the three steels.

All the data obtained for these steels are shown in tables V and VI. Many of the data points were obtained for purposes other than the application to time-temperature parameters, as described in this report. As already discussed in references 4 and 11, a much smaller amount of data is needed when an accelerated program is desired; however, since these data were already available, all the data indicated in tables V and VI were used to obtain the best possible parametric constants.

For all three steels the analysis showed the stress exponent q to be zero, but the temperature exponent r to be different for each of the three materials. For steel K the best value of r was 1, which indicated that the best fit is obtained by the linear parameter. For steel P a value of r of -1 was obtained, which indicated a parameter similar to the Larson-Miller parameter; however, the corresponding value of T_a was 200° F rather than -460° F used in the Larson-Miller parameter. For steel C the value of R was 2.5.

Figure 1 shows the results for steel K. Here the master curve consists of a plot of stress against the optimized parameter $(T - 300)/(\log t - 16.54)$.

Figure 2 shows the isothermals computed by using the optimized parameters, as shown on each of the figures. The range of the NASA data used to obtain these parameters is also shown on each of the figures. The data points shown are the German results obtained to date. The predictions up to 100 000 hours from the NASA data based on the optimized parameters agree well with the German data, if scatter and differences in testing technique between the two organizations are considered.

Figure 3 shows a comparison for each of the three steels between the best linear parameter, the best Larson-Miller parameter, and the best general parameter. Although for some of the steels fair agreement can be obtained with one or the other of these parameters, it is clear that the general parameter is superior when all the materials are considered jointly. If any one of the special cases of this parameter is to be chosen for all materials, the linear

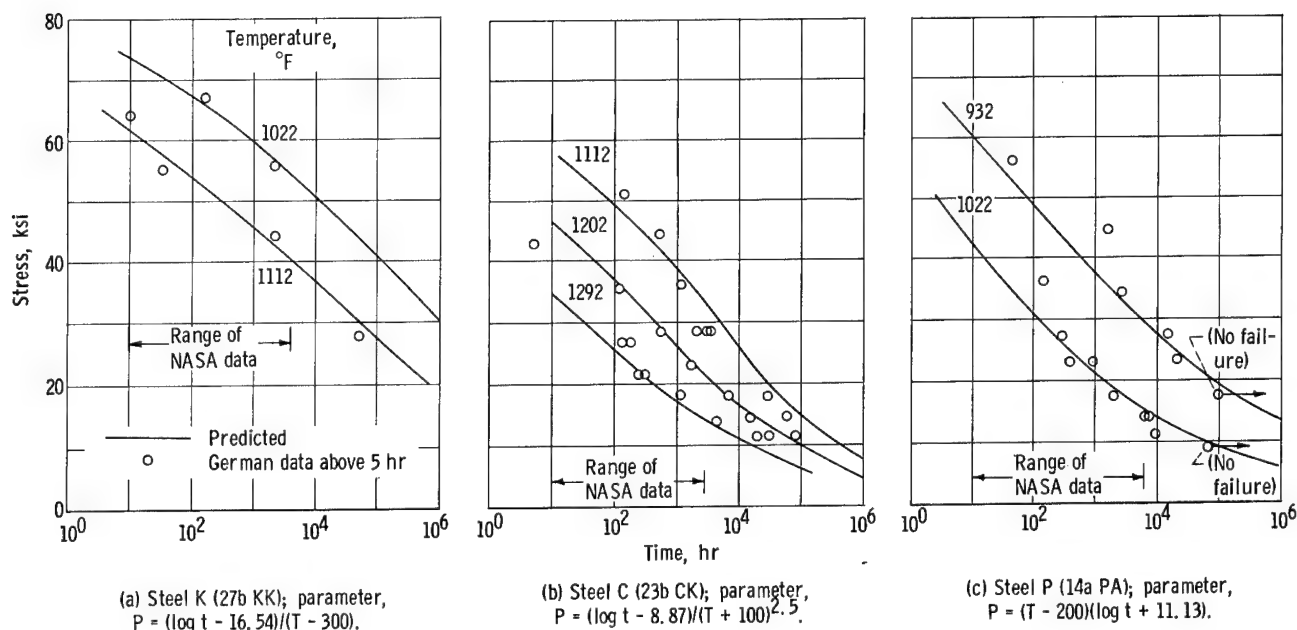


Figure 2. - Analysis of German steel data by generalized parameter with optimum constants (where T is temperature, and t is time to rupture).

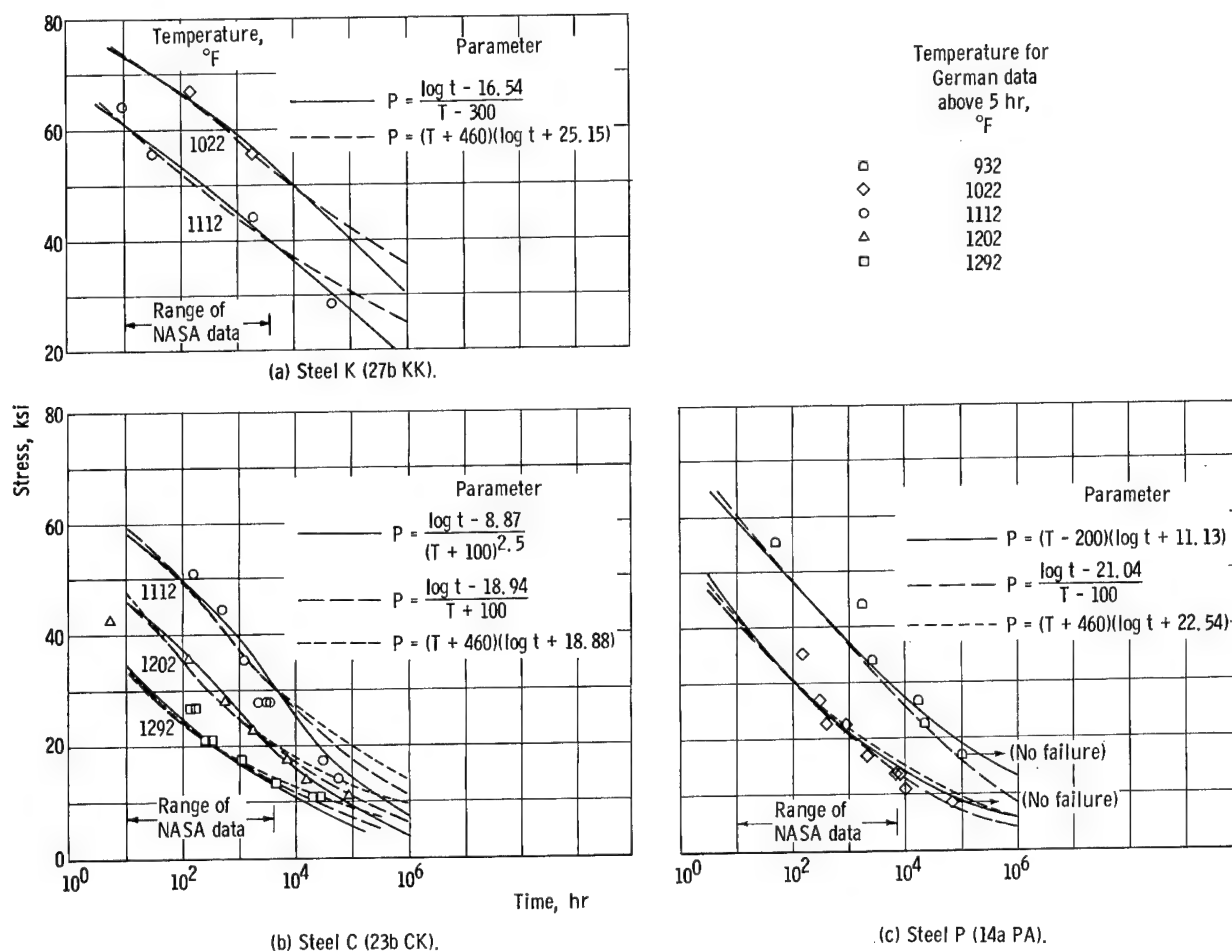
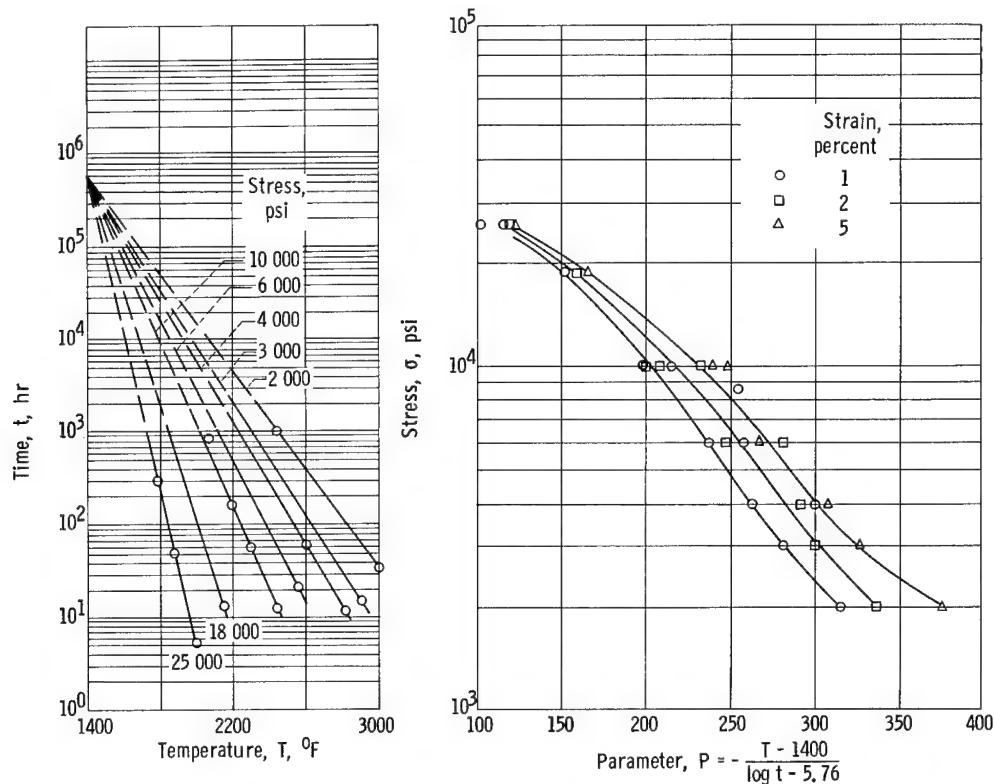


Figure 3. - Analysis of German steel data by several parameters (where T is temperature, and t is time to rupture).



(a) 5-Percent strain.

(b) Master curves obtained for 1-, 2-, and 5-percent strain.

Figure 4. - Analysis of creep data for columbium alloy FS-85 by linear parameter.

parameter would appear to be the best choice.

Application to Creep Data

Although there is no fundamental reason why the same parameter is capable of representing both creep and rupture data, it has nevertheless been found empirically (refs. 1 and 2) that the dual role of the same parameter leads to reasonable results. Experimental data for creep are much more limited, however, than that for rupture, and such data tend to contain more scatter, hence, analysis of creep data by the parametric approach has been limited in the past.

The method of the present report can be applied directly to creep data without any change. All that is necessary is to redefine t as the time to attain a specified amount of creep rather than as the rupture time. Thus, it is assumed that for a given amount of creep, say 1 percent, a plot of $\log \sigma$ against a parameter, such as that given by equation (1), will produce a single master curve. For a different amount of creep, say 5 percent, a different master curve can be obtained, but it is assumed that the parametric constants, such as $\log t_a$ and T_a , remain the same and that they equal the values obtained from rupture data.

Calculations of this type were performed for columbium alloy FS-85. The creep tests were limited to runs of approximately 1000 hours; the data are

given in table VII, as taken from reference 8. Figure 4(a) shows the data for 5-percent creep strain, and figure 4(b) shows the master curves obtained for 1-, 2-, and 5-percent strain as well as the parametric constants obtained by the method of this report. While scatter in the creep data is high, the correlation must be regarded as good. In general, the points agree well with the master curve.

Although these results are encouraging, much more work is necessary before it can be concluded that the parametric approach is completely valid for creep data. If it is eventually concluded that the parametric approach is valid for creep data and in particular that the parametric constants are the same for both the creep and rupture processes, it is obvious that a great saving in test facilities and test program planning will result. It therefore seems very worthwhile in future studies to give more attention to the correlation and extrapolation of creep data by the parametric method.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 3, 1965.

APPENDIX A

ORTHOGONAL POLYNOMIALS AND LEAST-SQUARES DETERMINATION OF PARAMETRIC CONSTANTS

A set of polynomials $Q_j(x)$ are said to be orthogonal over an interval with respect to the weighting function $\tau(x)$ if they satisfy the following relation

$$\int_{x=x_1}^{x=x_2} \tau^2(x) Q_j(x) Q_k(x) dx = 0 \quad j \neq k \quad (A1)$$

Similarly a set of polynomials can be defined to be orthogonal over a set of n discrete points x_i by the following relation

$$\sum_{i=1}^n \tau_i^2 Q_j(x_i) Q_k(x_i) = 0 \quad j \neq k \quad (A2)$$

It can be shown (ref. 6), that all orthogonal polynomials satisfy a three-term recurrence relation of the form

$$Q_{k+1} = (x - \alpha_k) Q_k - \beta_k Q_{k-1} \quad k \geq 1 \quad (A3)$$

Thus by starting with $Q_1 = 1$ and $\beta_1 = 0$ an infinite set of orthogonal polynomials can be generated by means of equation (A3) if values for α_k and β_k are known. These can be determined from the orthogonality conditions (eqs. (A1) or (A2)). From the relation (A2) it follows that

$$\sum_{i=1}^n \tau_i^2 Q_k(x_i) Q_{k+1}(x_i) = 0 \quad (A4a)$$

and

$$\sum_{i=1}^n \tau_i^2 Q_{k+1}(x_i) Q_{k-1}(x_i) = 0 \quad (A4b)$$

When the recurrence relation (A3) is used to eliminate Q_{k+1} , there is obtained

$$\sum_{i=1}^n \tau_i^2 Q_k \left[(x_i - \alpha_k) Q_k - \beta_k Q_{k-1} \right] = 0 \quad (A5a)$$

$$\sum_{i=1}^n \tau_i^2 [(x_i - \alpha_k) Q_k - \beta_k Q_{k-1}] Q_{k-1} = 0 \quad (A5b)$$

When the orthogonality condition (A2) is used, equations (A5a) and (A5b) reduce to

$$\sum_{i=1}^n \tau_i^2 (x_i - \alpha_k) Q_k^2 = 0 \quad (A6a)$$

$$\sum_{i=1}^n \tau_i^2 (x_i Q_k Q_{k-1} - \beta_k Q_{k-1}^2) = 0 \quad (A6b)$$

Solving equations (A6) for α_k and β_k gives

$$\alpha_k = \frac{\sum_{i=1}^n x_i \tau_i^2 Q_k^2}{\sum_{i=1}^n \tau_i^2 Q_k^2} \quad (A7a)$$

$$\beta_k = \frac{\sum_{i=1}^n x_i \tau_i^2 Q_k Q_{k-1}}{\sum_{i=1}^n \tau_i^2 Q_{k-1}^2} \quad (A7b)$$

Thus a set of orthogonal polynomials can be generated that are orthogonal over a finite set of discrete values of the variable x . Note that these values need not be equally spaced, a condition that is obviously necessary for stress-rupture data.

Scaling of Polynomial Argument

From the recurrence relation (A3) with $Q_1 = 1$, it follows that the leading term of $Q_{k+1}(x_i)$ is x_i^k . Therefore, depending on the values of x_i , the values of $Q_{k+1}(x_i)$ can become very large or very small. This procedure can lead to a loss of significant figures in performing the calculations. It is shown in reference 7, by comparison with the Chebyshev polynomials, that if x is scaled so that all the values of X_i lie between 2 and -2, the polynomial

values $Q_j(X_i)$ will all be of approximately uniform size. To perform this scaling, let x_{\max} be the maximum value of $\log \sigma$ and x_{\min} be the minimum value of $\log \sigma$; then let

$$X = A \log \sigma + B \quad (\text{A8})$$

$$2 = Ax_{\max} + B \quad (\text{A9a})$$

$$-2 = Ax_{\min} + B \quad (\text{A9b})$$

and solving for A and B results in equations (9b).

It has been found in practice that scaling the values of x as indicated does indeed preserve the significance of the calculations.

Least-Squares Procedure

In terms of the orthogonal polynomials, equation (3) can be written

$$y = \sigma^q y_a + \tau \sum_{j=1}^{m+1} u_j Q_j(X) \quad (\text{A10})$$

To find the best values of y_a and u_j that fit the data, the sum of the squares of the residuals is minimized. Thus let

$$S = \sum_{i=1}^n \left[y_i - \sigma_i^q y_a - \tau_i \sum_{j=1}^n u_j Q_j(X_i) \right]^2 \quad (\text{A11})$$

Then in order to find the values of y_a and u_j that will make S a minimum, S is differentiated in turn with respect to y_a and each u_j , and the resulting equations are set equal to zero. When this is done, the following set of equations is obtained:

$$\left. \begin{aligned} a_0 y_a + a_1 u_1 + a_2 u_2 + \dots + a_{m+1} u_{m+1} &= c_0 \\ a_1 y_a + b_1 u_1 + 0 + \dots + 0 &= c_1 \\ a_2 y_a + 0 + b_2 u_2 + \dots + 0 &= c_2 \\ \vdots & \\ a_{m+1} y_a + 0 + 0 + \dots + b_{m+1} u_{m+1} &= c_{m+1} \end{aligned} \right\} \quad (\text{A12})$$

where

$$\left. \begin{aligned}
a_0 &= \sum_{i=1}^n \sigma_i^{2q} \\
a_j &= \sum_{i=1}^n \sigma_i^q \tau_i Q_j(X_i) \quad j = 1, 2, \dots, m+1 \\
b_j &= \sum_{i=1}^n \tau_i^2 Q_j^2(X_i) \quad j = 1, 2, \dots, m+1 \\
c_0 &= \sum_{i=1}^n \sigma_i^q y_i \\
c_j &= \sum_{i=1}^n \tau_i y_i Q_j(X_i) \quad j = 1, 2, \dots, m+1
\end{aligned} \right\} \quad (A13)$$

It is to be noted that the only nonzero elements in the coefficient matrix of equations (A12) are the diagonal elements and the elements of the first row and first column. All the other elements are zero because of the orthogonality properties of the polynomials used. This is one of the major advantages in using orthogonal polynomials. In the usual case of data fitting, all the elements of the first row and first column, except for the first element, would also be zero; and the equations would be completely uncoupled, each u_j being computed completely independent of the others, without the necessity of solving any sets of equations with the resultant loss of significant figures. In this particular case because of the added constant y_a , the equations are not completely uncoupled, but they are very nearly uncoupled and can readily be solved. Thus for any equation after the first

$$u_j = \frac{c_j - a_j y_a}{b_j} \quad (A14)$$

Substituting into the first equation and solving for y_a give immediately

$$y_a = \frac{c_0 - \sum_{j=1}^{m+1} \frac{a_j c_j}{b_j}}{a_0 - \sum_{j=1}^{m+1} \frac{a_j^2}{b_j}} \quad (A15)$$

APPENDIX B

FORTRAN IV PROGRAM

```

$ID      YAG1202 ERNEST ROBERTS, JR. - 140 M-S - PAX 6132
$LIBSIO      CONTINUE
$IBJOB      SOURCE
$IBFTC PRMTR1 LIST,REF,DECK
C          CREEP/STRESS-RUPTURE PARAMETER PROGRAM
C
C          NOMENCLATURE IS AS FOLLOWS
C
C      DD          STANDARD DEVIATION
C      KK          DEGREE OF FREEDOM
C      KM          NUMBER OF VALUES OF M READ
C      KQ          NUMBER OF VALUES OF Q READ
C      KR          NUMBER OF VALUES OF R READ
C      KTA         NUMBER OF VALUES OF TTA READ
C      M           DEGREE POLYNOMIAL
C      N           NUMBER OF DATA POINTS
C      PP          PARAMETER
C      Q           STRESS EXPONENT
C      QQ          POLYNOMIAL
C      R           TEMPERATURE EXPONENT
C      RATIO       ABS(Y-YY)/DD
C      SIGMA       STRESS
C      SIGQ        SIGMA**Q
C      T           TIME
C      TA          TIME INTERCEPT
C      TAU         SIGMA**Q*(TT-TTA)**R
C      TAUSQR      TAU**2
C      TIME        CALCULATED T (10.**YY)
C      TT          TEMPERATURE
C      TTA         TEMPERATURE INTERCEPT
C      X           LOG SIGMA
C      Y           LOG T
C      YA          LOG TA
C      YY          CALCULATED LOG T
C
C          ALL QUANTITIES IN COMMON WITH THIS PROGRAM AND THIS PAPER
C          ARE REPRESENTED BY THE SAME SYMBOL, WITH REPEATED
C          LETTERS INDICATING THE UPPER CASE AND GREEK LETTERS BEING SPELLED-
C          OUT.
C
C          PROGRAM EXTRAPOLATES CREEP/STRESS-RUPTURE DATA USING A
C          GENERALIZED PARAMETER
C           $PP = (Y/SIGMA**Q - YA)/(TT - TTA)**R$ ,
C          SELECTS PARAMETER PRODUCING SMALLEST RESIDUAL AND OUTPUTS A
C          COMPLETE TABLE. RESULTS OF ALL OTHER VALUES ARE SUMMARIZED IN
C          A SHORTER TABLE.
C
C          *****INPUT*****
C
C          TITLE CARD, MODE CARD, AND FIVE (5) SETS OF DATA. AT THE END OF
C          EACH SET OF DATA MUST BE A CARD WITH THE WORD 'END' IN THE FIRST
C          THREE COLUMNS. ALL DATA CARDS (EXCEPTING TITLE AND MODE CARDS)
C          MUST HAVE BLANKS IN THE FIRST THREE COLUMNS. COLUMNS 73-80 ARE
C          INGORED.
C
C          TITLE - ANY ALPHAMERIC INFORMATION--HEADS EACH PAGE OF OUTPUT
C
C          MODE CARD - ONE OF THREE WORDS IN COLUMNS 1-6, 'LARSON', 'LINEAR',
C          OR 'GENRAL'. THIS CARD DEFINES 'KK', THE DEGREE OF
C          FREEDOM, USED IN CALCULATING GOODNESS OF FIT.
C
C          DATA SET 1--VALUES OF TTA TO BE INVESTIGATED--ONE PER CARD

```

PRMT	1
PRMT	2
PRMT	3
PRMT	4
PRMT	5
PRMT	6
PRMT	7
PRMT	8
PRMT	9
PRMT	10
PRMT	11
PRMT	12
PRMT	13
PRMT	14
PRMT	15
PRMT	16
PRMT	17
PRMT	18
PRMT	19
PRMT	20
PRMT	21
PRMT	22
PRMT	23
PRMT	24
PRMT	25
PRMT	26
PRMT	27
PRMT	28
PRMT	29
PRMT	30
PRMT	31
PRMT	32
PRMT	33
PRMT	34
PRMT	35
PRMT	36
PRMT	37
PRMT	38
PRMT	39
PRMT	40
PRMT	41
PRMT	42
PRMT	43
PRMT	44
PRMT	45
PRMT	46
PRMT	47
PRMT	48
PRMT	49
PRMT	50
PRMT	51
PRMT	52
PRMT	53
PRMT	54
PRMT	55
PRMT	56
PRMT	57
PRMT	58

C	FORMAT (3X,F10.0)--50 VALUES MAXIMUM	PRMT 59
C		PRMT 60
C	DATA SET 2--VALUES OF TEMPERATURE EXPONENT, R, TO BE INVESTIGATED	PRMT 61
C	ONE PER CARD--FORMAT (3X,F10.0)--20 VALUES MAXIMUM	PRMT 62
C		PRMT 63
C	DATA SET 3--VALUES OF STRESS EXPONENT, Q, TO BE INVESTIGATED	PRMT 64
C	ONE PER CARD--FORMAT (3X,F10.0)--20 VALUES MAXIMUM	PRMT 65
C		PRMT 66
C	DATA SET 4--DEGREES OF POLYNOMIAL, M, TO BE INVESTIGATED	PRMT 67
C	ONE PER CARD--FORMAT (3X,I2)--MAXIMUM VALUE NOT TO	PRMT 68
C	EXCEED 20--ZERO MAY NOT BE USED.	PRMT 69
C		PRMT 70
C	DATA SET 5--DATA POINTS IN THE ORDER TEMPERATURE, STRESS, AND	PRMT 71
C	TIME--ONE SET PER CARD--FORMAT (3X,3F10.0)	PRMT 72
C	THE VALUE OF STRESS IS AUTOMATICALLY DIVIDED BY 1000	PRMT 73
C	FOR ALL CALCULATIONS EXCEPT FINDING THE LOG STRESS.	PRMT 74
C	200 SETS MAXIMUM.	PRMT 75
C		PRMT 76
C	*****REPEAT*****	PRMT 77
C		PRMT 78
C	EACH OF THE FIVE SETS OF DATA MUST BE FOLLOWED BY A CARD HAVING	PRMT 79
C	THE WORD END IN THE FIRST THREE COLUMNS.	PRMT 80
C	ALL DATA CARDS (EXCEPTING TITLE AND MODE CARDS) MUST HAVE THE	PRMT 81
C	FIRST THREE COLUMNS BLANK.	PRMT 82
C		PRMT 83
C	WITHIN EACH SET, DATA MAY BE IN ANY ORDER. IT WILL BE PROCESSED	PRMT 84
C	IN THE ORDER PRESENTED TO THE MACHINE.	PRMT 85
C		PRMT 86
C	THE CALCULATIONS ARE PERFORMED IN FOUR (4) LOOPS.	PRMT 87
C	GOING FROM INNERMOST TO OUTERMOST, THE QUANTITIES ARE VARIED	PRMT 88
C	IN THE FOLLOWING ORDER	PRMT 89
C	DEGREE POLYNOMIAL, M	PRMT 90
C	VALUE OF TTA	PRMT 91
C	TEMPERATURE EXPONENT, R	PRMT 92
C	STRESS EXPONENT, Q	PRMT 93
C		PRMT 94
C	THE OUTPUT TABLES UTILIZE LESS THAN 120 COLUMNS ON THE PRINTER	PRMT 95
C	AND EXPECT NO CARRIAGE CONTROLS OTHER THAN 1, 0, + AND BLANK.	PRMT 96
C	A LINE COUNTER IS INCORPORATED TO LIMIT OUTPUT TO 60 LINES PER	PRMT 97
C	PAGE. FOR EACH NEW PAGE THE TITLE AND APPROPRIATE COLUMN HEADINGS	PRMT 98
C	ARE PRINTED. PROGRAM ENDS WITH A TRANSFER TO THE INITIAL READ.	PRMT 99
C		PRMT 100
C	PAGE COUNTING AND ERROR TRAPS MUST BE PROVIDED BY THE OPERATING	PRMT 101
C	SYSTEM.	PRMT 102
C		PRMT 103
C	PROGRAM WITH IBSYS AND IOCSM WILL RUN ON A 16K MACHINE	PRMT 104
C		PRMT 105
C		PRMT 106
C	LOGICAL TRGGR1, TRGGR2, TRGGR3	PRMT 107
C		PRMT 108
C	DIMENSION TITL(12),TABLE(6,110),ITBL(6,110)	PRMT 109
C		PRMT 110
C	EQUIVALENCE (TABLE(1,1),ITBL(1,1))	PRMT 111
C		PRMT 112
C	COMMON /DATA/SIGMA(201),T(201),TT(201)	PRMT 113
C	1 /TRYS/M(21),Q(51),R(51),TTA(51)	PRMT 114
C	2 /FDATA/SIGQ(200),TAU(200),TAUSQR(200),X(200),XX(200),Y(200)	PRMT 115
C	3 /CALC/PP(200),RATIO(200),TIME(200),YY(200)	PRMT 116
C	4 /END/LND/N/N/DD/DD/DEGREE/DEGREE	PRMT 117
C	5 /PLYNML/OTHER1(4221),YA,OTHER2(63)	PRMT 118
C		PRMT 119
C		PRMT 120
C	INPUT	PRMT 121
C		PRMT 122
C		PRMT 123
C	1 WRITE (6,9999)	PRMT 124
C	READ (5,9001) (TITL(K),K=1,12)	

	READ (5,9001) DEGREE	PRMT 125
	K = 0	PRMT 126
10	K = K+1	PRMT 127
	READ (5,9002) CHECK,TTA(K)	PRMT 128
	IF (CHECK.NE.END) GO TO 10	PRMT 129
	KTA = K-1	PRMT 130
	K = 0	PRMT 131
15	K = K+1	PRMT 132
	READ (5,9002) CHECK,R(K)	PRMT 133
	IF (CHECK.NE.END) GO TO 15	PRMT 134
	KR = K-1	PRMT 135
	K = 0	PRMT 136
20	K = K+1	PRMT 137
	READ (5,9002) CHECK,Q(K)	PRMT 138
	IF (CHECK.NE.END) GO TO 20	PRMT 139
	KQ = K-1	PRMT 140
	K = 0	PRMT 141
25	K = K+1	PRMT 142
	READ (5,9003) CHECK,M(K)	PRMT 143
	IF (CHECK.NE.END) GO TO 25	PRMT 144
	KM = K-1	PRMT 145
	K = 0	PRMT 146
30	K = K+1	PRMT 147
	READ (5,9004) CHECK,TT(K),SIGMA(K),T(K)	PRMT 148
	IF (CHECK.NE.END) GO TO 30	PRMT 149
	N=K-1	PRMT 150
C		PRMT 151
C	END OF INPUT	PRMT 152
C		PRMT 153
C	FIND LOG STRESS AND LOG TIME	PRMT 154
C		PRMT 155
	DO 100 K=1,N	PRMT 156
	X(K)=ALOG10(SIGMA(K))+3.	PRMT 157
	Y(K)=ALOG10(T(K))	PRMT 158
100	CONTINUE	PRMT 159
C		PRMT 160
C	INITIALIZE CONSTANTS	PRMT 161
C		PRMT 162
	DD1=1.E5	PRMT 163
	LINES=51	PRMT 164
	TRGGR3=.FALSE.	PRMT 165
	NTRY=0	PRMT 166
C		PRMT 167
C	SCALE LOGS OF STRESS	PRMT 168
C		PRMT 169
	CALL SCALE	PRMT 170
C		PRMT 171
C	FIND HIGHEST DEGREE POLYNOMIAL	PRMT 172
C		PRMT 173
	MAX = 0	PRMT 174
	DO 110 K=1,KM	PRMT 175
	MAX = MAX0(MAX,M(K))	PRMT 176
110	CONTINUE	PRMT 177
C		PRMT 178
C	MAJOR LOOP - CALCULATES ALL Y(A)'S AND RESIDUALS	PRMT 179
C	WRITES SUMMARY TABLE	PRMT 180
C	FINDS SMALLEST RESIDUAL	PRMT 181
C		PRMT 182
	DO 500 K5=1,KQ	PRMT 183
C		PRMT 184
C	CALCULATE SIGMA**Q	PRMT 185
C		PRMT 186
	DO 112 K=1,N	PRMT 187
	SIGQ(K)=SIGMA(K)**Q(K5)	PRMT 188
112	CONTINUE	PRMT 189
	DO 400 K4=1,KR	PRMT 190

C	DO 300 K3=1,KTA	PRMT 191
C		PRMT 192
C	CALCULATE TAU AND TAU**2	PRMT 193
C		PRMT 194
	DO 120 K=1,N	PRMT 195
	TDIFF=ABS(TT(K)-TTA(K3))	PRMT 196
	IF (TDIFF) 118,115,118	PRMT 197
115	TAU(K)=0.	PRMT 198
	GO TO 119	PRMT 199
118	TAU(K)=SIGQ(K)*TDIFF**R(K4)	PRMT 200
119	TAUSQR(K) = TAU(K)**2	PRMT 201
120	CONTINUE	PRMT 202
C		PRMT 203
C	EVALUATE POLYNOMIALS	PRMT 204
C		PRMT 205
	CALL POLY(MAX)	PRMT 206
C		PRMT 207
	DO 200 K2=1,KM	PRMT 208
C		PRMT 209
C	DETERMINE Y(A)	PRMT 210
C		PRMT 211
	CALL YSUBA (M(K2))	PRMT 212
C		PRMT 213
C	CALCULATE THEORETICAL LOG TIMES AND TIMES	PRMT 214
C		PRMT 215
	CALL YTH(M(K2))	PRMT 216
C		PRMT 217
C	COMPUTE RESIDUAL	PRMT 218
C		PRMT 219
	CALL RESID(M(K2))	PRMT 220
C		PRMT 221
C	MAKE ONE ENTRY IN SUMMARY TABLE	PRMT 222
C		PRMT 223
	NTRY=NTRY+1	PRMT 224
	TABLE(1,NTRY)=Q(K5)	PRMT 225
	TABLE(2,NTRY)=R(K4)	PRMT 226
	ITBLE(3,NTRY)=M(K2)	PRMT 227
	TABLE(4,NTRY)=TTA(K3)	PRMT 228
	TABLE(5,NTRY)=YA	PRMT 229
	TABLE(6,NTRY)=DD	PRMT 230
	TRGGR2=NTRY.EQ.2*LINES	PRMT 231
	IF (TRGGR2) GO TO 170	PRMT 232
	GO TO 190	PRMT 233
C		PRMT 234
C	OUTPUTS ONE PAGE OF SUMMARY TABLE	PRMT 235
C		PRMT 236
C		PRMT 237
C	OUTPUT TITLE AND HEADINGS FOR SUMMARY TABLE	PRMT 238
C		PRMT 239
170	WRITE (6,9005) (TITLE(K),K=1,12),DEGREE	PRMT 240
	IF (LINES.EQ.51) WRITE (6,9006) KTA,KR,KO,KM,N	PRMT 241
	WRITE (6,9007)	PRMT 242
	TRGGR1=NTRY.LE.LINES	PRMT 243
	LIMIT=LINES	PRMT 244
	IF (TRGGR1) LIMIT=NTRY	PRMT 245
	DO 180 K=1,LIMIT	PRMT 246
	WRITE (6,9008) (TABLE(I,K),I=1,2),ITBLE(3,K),(TABLE(I,K),I=4,6)	PRMT 247
	IF (TRGGR1) GO TO 180	PRMT 248
	KOL2=K+LINES	PRMT 249
	IF (TRGGR2) GO TO 175	PRMT 250
	IF (KOL2.GT.NTRY) GO TO 180	PRMT 251
175	WRITE (6,9009) (TABLE(I,KOL2),I=1,2),ITBLE(3,KOL2),	PRMT 252
1	(TABLE(I,KOL2),I=4,6)	PRMT 253
180	CONTINUE	PRMT 254
	NTRY=0	PRMT 255
	LINES=55	PRMT 256

	IF (TRGGR3) GO TO 1000	PRMT 257
C		PRMT 258
C	SAVE VALUES PRODUCING SMALLEST RESIDUAL	PRMT 259
C		PRMT 260
190	IF (DD1.LE.DD) GO TO 200	PRMT 261
	M1 = M(K2)	PRMT 262
	TTA1=TTA(K3)	PRMT 263
	R1 = R(K4)	PRMT 264
	Q1 = Q(K5)	PRMT 265
	YA1 = YA	PRMT 266
	DD1=DD	PRMT 267
200	CONTINUE	PRMT 268
300	CONTINUE	PRMT 269
400	CONTINUE	PRMT 270
500	CONTINUE	PRMT 271
	TRGGR3=.TRUE.	PRMT 272
	IF (NTRY.NE.0) GO TO 170	PRMT 273
C		PRMT 274
C	END MAJOR LOOP	PRMT 275
C		PRMT 276
C	OUTPUT OPTIMUM VALUES AND HEADING FOR FULL TABLE	PRMT 277
C		PRMT 278
1000	CONTINUE	PRMT 279
1010	WRITE (6,9005) (TITLE(K),K=1,12),DEGREE	PRMT 280
	LINES=3	PRMT 281
1020	WRITE (6,9010) Q1,R1,M1,TTA1,YA1,DD1	PRMT 282
	LINES=LINES+5	PRMT 283
1030	WRITE (6,9011)	PRMT 284
	LINES=LINES+3	PRMT 285
C		PRMT 286
C	CALCULATE THEORETICAL TIMES, RATIOS OF DIFFERENCES	PRMT 287
C	TO RESIDUAL, AND VALUES OF THE PARAMETER, FOR THE	PRMT 288
C	PARAMETER PRODUCING THE MINIMUM RESIDUAL	PRMT 289
C		PRMT 290
	DO 1035 K=1,N	PRMT 291
	TDIFF=ABS(TT(K)-TTA1)	PRMT 292
	SIGQ(K)=SIGMA(K)**Q1	PRMT 293
	IF (TDIFF) 1032,1031,1032	PRMT 294
1031	TAU(K)=0.	PRMT 295
	GO TO 1034	PRMT 296
1032	TAU(K)=SIGQ(K)*TDIFF**R1	PRMT 297
1034	TAUSQR(K) = TAU(K)**2	PRMT 298
1035	CONTINUE	PRMT 299
	DD=DD1	PRMT 300
	CALL POLY(M1)	PRMT 301
	CALL YSUBA(M1)	PRMT 302
	CALL YTH (M1)	PRMT 303
	CALL RATIO1	PRMT 304
	CALL PARAM	PRMT 305
C		PRMT 306
C	OUTPUT FULL TABLE	PRMT 307
C		PRMT 308
	K = 0	PRMT 309
1040	K = K+1	PRMT 310
	WRITE (6,9012) TT(K),SIGMA(K),X(K),T(K),TIME(K),Y(K),YY(K),	PRMT 311
1	RATIO(K),PP(K)	PRMT 312
	LINES=LINES+1	PRMT 313
	IF (K.EQ.N) GO TO 1	PRMT 314
	IF (LINES.LT.60) GO TO 1040	PRMT 315
	WRITE (6,9005) (TITLE(KKK),KKK=1,12),DEGREE	PRMT 316
	WRITE (6,9011)	PRMT 317
	LINES=6	PRMT 318
	GO TO 1040	PRMT 319
C		PRMT 320
C	END OF PROGRAM	PRMT 321
C		PRMT 322

C		PRMT 323
C	FORMAT STATEMENTS FOR PROGRAM	PRMT 324
C		PRMT 325
C	FORMATS FOR INPUT	PRMT 326
C		PRMT 327
	9001 FORMAT (12A6)	PRMT 328
	9002 FORMAT (A3,F10.0)	PRMT 329
	9003 FORMAT (A3,I2)	PRMT 330
	9004 FORMAT (A3,0PF10.0,3PF10.0,0PF10.0)	PRMT 331
C		PRMT 332
C	FORMATS FOR OUTPUT	PRMT 333
C		PRMT 334
C	TITLE (SKIPS TO NEW PAGE)	PRMT 335
C		PRMT 336
	9005 FORMAT(1H1,20X,12A6/1H ,30X,A6,10H PARAMETER/1H)	PRMT 337
C		PRMT 338
C	SUMMARY OF INPUT	PRMT 339
C		PRMT 340
	9006 FORMAT (1H ,10X,45HCREEP/RUPTURE PARAMETERS ARE INVESTIGATED FOR/	PRMT 341
	11H ,I2,18H VALUE(S) OF T(A),,I3,25H TEMPERATURE EXPONENT(S),,I3,	PRMT 342
	224H STRESS EXPONENT(S), AND,I3,14H POLYNOMIAL(S)/1H ,10X,5HUSING,	PRMT 343
	314,12H DATA POINTS/1H)	PRMT 344
C		PRMT 345
C	HEADINGS FOR SUMMARY TABLE, ONE LINE OF SUMMARY TABLE	PRMT 346
C		PRMT 347
	9007 FORMAT (1H ,2(2X,1HQ,7X,1HR,6X,1HM,5X,4HT(A),5X,4HY(A),4X,	PRMT 348
	1 8HSTD.DEV.,10X)/1H)	PRMT 349
	9008 FORMAT (1H ,0PF5.2,F8.2,I5,F9.0,F10.2,1PE11.2)	PRMT 350
	9009 FORMAT (1H+,58X,0PF5.2,F8.2,I5,F9.0,F10.2,1PE11.2)	PRMT 351
C		PRMT 352
C	OPTIMUM VALUES	PRMT 353
C		PRMT 354
	9010 FORMAT(1H 10X44HVALUES PRODUCING SMALLEST STANDARD DEVIATION/3HQ=PRMT	PRMT 355
	1F5.2,4H, R=F5.2,4H, M=I2,7H, T(A)=F6.0,7H, Y(A)=F9.3,11H, STD.DEV.	PRMT 356
	2=1PE9.2/1H0)	PRMT 357
C		PRMT 358
C	HEADINGS FOR FULL TABLE, ONE LINE OF FULL TABLE	PRMT 359
C		PRMT 360
	9011 FORMAT (5H TEMP,4X,6HSTRESS,3X,3HLOG,6X,4HTIME,5X,6HCALCID,5X,	PRMT 361
	13HLOG,3X,8HCALC LOG,2X6HDEV/SQ,3X,9HPARAMETER/1H ,8X,6H(*E-3),2X,	PRMT 362
	26HSTRESS,14X,4HTIME,5X,4HTIME,4X,4HTIME/1H)	PRMT 363
	9012 FORMAT (1H ,0PF5.0,F8.1,F8.3,2F10.1,3F9.3,1PE12.3)	PRMT 364
C		PRMT 365
	9999 FORMAT (1H1)	PRMT 366
C		PRMT 367
	END	PRMT 368

\$IBFIC PRMBLK LIST,REF,DECK		
C SETS FIRST POLYNOMIAL TO UNITY AT ALL STATIONS AND STORES	PRMB	1
C ALPHAMERIC CODE WORDS	PRMB	2
C	PRMB	3
BLOCK DATA	PRMB	4
COMMON /PLYNML/QQ(21,200),OTHERS(85)/END/END/NAMES/NAMES(2)	PRMB	5
DATA (QQ(1,K),K=1,200)/200*1./,END/3HEND/,	PRMB	6
1 (NAMES(K),K=1,2)/12HLARSONLINEAR/	PRMB	7
END	PRMB	8

\$IBFTC PARAM LIST,REF,DECK		
C SUBROUTINE FOR EVALUATING THE PARAMETER AT EACH POINT	PARAM	1
C	PARAM	2
SUBROUTINE PARAM	PARAM	3
C	PARAM	4
COMMON /FDATA/SIGQ(200),TAU(200),OTHERS(600),Y(200)	PARAM	5
1 /CALC/PP(200),OTHER1(600)/N/N	PARAM	6
2 /PLYNML/OTHER2(4221),YA,OTHER3(63)	PARAM	7
C	PARAM	8
DO 10 K=1,N	PARAM	9
PP(K) = (Y(K)-SIGQ(K)*YA)/TAU(K)	PARAM	10
10 CONTINUE	PARAM	11
RETURN	PARAM	12
END	PARAM	13

\$IBFTC YTH LIST,REF,DECK		
C SUBROUTINE FOR CALCULATING TIMES AND LOG TIMES FROM THE PARAMETER	YTH	1
C	YTH	2
SUBROUTINE YTH(M)	YTH	3
C	YTH	4
COMMON /CALC/OTHERS(400),TIME(200),YY(200)	YTH	5
1 /FDATA/SIGQ(200),TAU(200),OTHER1(800)	YTH	6
2 /PLYNML/QQ(21,200),U(21),YA,OTHER2(63)	YTH	7
3 /N/N	YTH	8
C	YTH	9
DO 10 K=1,N	YTH	10
YY(K) = 0.	YTH	11
10 CONTINUE	YTH	12
M1 = M+1	YTH	13
DO 30 K=1,N	YTH	14
DO 20 J=1,M1	YTH	15
YY(K) = YY(K)+QQ(J,K)*U(J)	YTH	16
20 CONTINUE	YTH	17
YY(K) = TAU(K)*YY(K)+SIGQ(K)*YA	YTH	18
TIME(K) = 10.**YY(K)	YTH	19
30 CONTINUE	YTH	20
RETURN	YTH	21
END	YTH	22

\$IBFTC RATIO1 LIST,REF,DECK		
C	SUBROUTINE FOR CALCULATING RATIOS	RATO 1
C	OF INDIVIDUAL RESIDUALS TO ROOT-MEAN-SQUARE RESIDUAL	RATO 2
C		RATO 3
	SUBROUTINE RATIO1	RATO 4
C		RATO 5
	COMMON /FDATA/OTHERS(1000),Y(200)	RATO 6
1	/CALC/OTHER1(200),RATIO(200),OTHER2(200),YY(200)	RATO 7
2	/N/N/DD/DD	RATO 8
C		RATO 9
	DO 10 K=1,N	RATO 10
	RATIO(K) = ABS(Y(K)-YY(K))/DD	RATO 11
10	CONTINUE	RATO 12
	RETURN	RATO 13
	END	RATO 14
\$IBFTC RESID LIST,REF,DECK		
C	SUBROUTINE FOR CALCULATING RESIDUAL	RESD 1
C		RESD 2
C	THE RESIDUAL IS BASED ON THE LOG OF THE TIME.	RESD 3
C	IT IS DEFINED AS THE SQUARE ROOT OF THE SUM OF THE SQUARES OF	RESD 4
C	THE INDIVIDUAL RESIDUALS DIVIDED BY THE DIFFERENCE BETWEEN THE NUM	RESD 5
C	BER OF DATA POINTS AND THE DEGREES OF FREEDOM. THE DEGREES OF	RESD 6
C	FREEDOM, KK, DEPENDS ON THE PARAMETER (SEE MAIN BODY OF REPORT).	RESD 7
C	KK=2 FOR LARSON-MILLER PARAMETER	RESD 8
C	KK=3 FOR LINEAR PARAMETER	RESD 9
C	KK=5 FOR GENERAL PARAMETER	RESD 10
C		RESD 11
C	DD = SQRT((Y-YY)**2/(N-M-KK))	RESD 12
C		RESD 13
	SUBROUTINE RESID(M)	RESD 14
C		RESD 15
	COMMON /FDATA/OTHERS(1000),Y(200)	RESD 16
1	/CALC/OTHER1(600),YY(200)	RESD 17
2	/DD/DD/N/N/DEGREE/DEGREE/NAMES/FAMES(2)	RESD 18
C		RESD 19
	IF (DEGREE.EQ.FAMES(2)) GO TO 20	RESD 20
	IF (DEGREE.EQ.FAMES(1)) GO TO 10	RESD 21
	KK = 5	RESD 22
	GO TO 30	RESD 23
10	KK = 2	RESD 24
	GO TO 30	RESD 25
20	KK = 3	RESD 26
30	D = N-M-KK	RESD 27
	DD = 0.	RESD 28
	DO 40 K=1,N	RESD 29
	DD = DD+(Y(K)-YY(K))**2	RESD 30
40	CONTINUE	RESD 31
	DD = SQRT(DD/D)	RESD 32
	RETURN	RESD 33
	END	RESD 34

\$IBFTC	YSUBA	LIST,REF,DECK	
C		SUBROUTINE FOR EVALUATING Y(A)	YSUB 1
C			YSUB 2
C		THIS SUBROUTINE ALSO EVALUATES THE QUANTITIES, U, NECESSARY	YSUB 3
C		FOR DETERMINING THE THEORETICAL LOG TIMES.	YSUB 4
C			YSUB 5
C		SUBROUTINE YSUBA(M)	YSUB 6
C			YSUB 7
	COMMON	/PLYNML/ QQ(21,200),U(21),YA,A(21),B(21),C(21)	YSUB 8
1		/FDATA/SIGQ(200),TAU(200),TAUSQR(200),OTHERS(400),	YSUB 9
2		Y(200)/N/N	YSUB 10
C			YSUB 11
	A0	= 0.	YSUB 12
	C0	= 0.	YSUB 13
		DO 10 K=1,N	YSUB 14
	A0	= A0+SIGQ(K)**2	YSUB 15
	C0	= C0+SIGQ(K)*Y(K)	YSUB 16
10		CONTINUE	YSUB 17
	M1	= M+1	YSUB 18
		DO 20 J=1,M1	YSUB 19
	A(J)	= 0.	YSUB 20
	B(J)	= 0.	YSUB 21
	C(J)	= 0.	YSUB 22
20		CONTINUE	YSUB 23
		DO 40 J=1,M1	YSUB 24
		DO 30 K=1,N	YSUB 25
	A(J)	= A(J)+SIGQ(K)*TAU(K)*QQ(J,K)	YSUB 26
	B(J)	= B(J)+TAUSQR(K)*QQ(J,K)**2	YSUB 27
	C(J)	= C(J) + TAU(K)*Y(K)*QQ(J,K)	YSUB 28
30		CONTINUE	YSUB 29
40		CONTINUE	YSUB 30
	SUM1	= 0.	YSUB 31
	SUM2	= 0.	YSUB 32
		DO 50 J=1,M1	YSUB 33
	AOB	= A(J)/B(J)	YSUB 34
	SUM1	= SUM1+AOB*C(J)	YSUB 35
	SUM2	= SUM2+AOB*A(J)	YSUB 36
50		CONTINUE	YSUB 37
	YA	=(C0-SUM1)/(A0-SUM2)	YSUB 38
		DO 60 J=1,M1	YSUB 39
	U(J)	=(C(J)-A(J)*YA)/B(J)	YSUB 40
60		CONTINUE	YSUB 41
		RETURN	YSUB 42
		END	YSUB 43

\$IBFTC POLY	LIST,REF,DECK	
C	SUBROUTINE FOR EVALUATING ORTHOGONAL POLYNOMIALS	POLY 1
C		POLY 2
C	ALL POLYNOMIALS UP TO MAXIMUM DESIRED DEGREE ARE EVALUATED	POLY 3
C	AT EACH DATA POINT	POLY 4
C		POLY 5
C	THE FIRST POLYNOMIAL IS IDENTICALLY EQUAL TO UNITY	POLY 6
C	THESE VALUES ARE STORED BY A BLOCK DATA SUBROUTINE	POLY 7
C		POLY 8
	SUBROUTINE POLY(M)	POLY 9
C		POLY 10
	COMMON /FDATA/OTHER1(400),TAUSQR(200),OTHER2(200),XX(200),	POLY 11
1	OTHER3(200)	POLY 12
2	/PLYNML/QQ(21,200),OTHERS(45),ALPHA(20),BETA(20)	POLY 13
3	/N/N	POLY 14
C		POLY 15
	S1 = 0.	POLY 16
	S2 = 0.	POLY 17
	DO 10 K=1,N	POLY 18
	S1 = S1+XX(K)*TAUSQR(K)	POLY 19
	S2 = S2+TAUSQR(K)	POLY 20
10	CONTINUE	POLY 21
	ALPHA(1) = S1/S2	POLY 22
	DO 20 K=1,N	POLY 23
	QQ(2,K) = XX(K)-ALPHA(1)	POLY 24
20	CONTINUE	POLY 25
	IF (M.LE.1) RETURN	POLY 26
	DO 50 K=2,M	POLY 27
	S1 = 0.	POLY 28
	S2 = 0.	POLY 29
	S3 = 0.	POLY 30
	S4 = 0.	POLY 31
	DO 30 J=1,N	POLY 32
	D1 = TAUSQR(J)*QQ(K,J)	POLY 33
	D2 = D1*QQ(K,J)	POLY 34
	S1 = S1+XX(J)*D2	POLY 35
	S2 = S2+D2	POLY 36
	S3 = S3+XX(J)*D1*QQ(K-1,J)	POLY 37
	S4 = S4+TAUSQR(J)*QQ(K-1,J)**2	POLY 38
30	CONTINUE	POLY 39
	ALPHA(K) = S1/S2	POLY 40
	BETA(K) = S3/S4	POLY 41
	DO 40 J=1,N	POLY 42
	QQ(K+1,J) = (XX(J)-ALPHA(K))*QQ(K,J)-BETA(K)*QQ(K-1,J)	POLY 43
40	CONTINUE	POLY 44
50	CONTINUE	POLY 45
	RETURN	POLY 46
	END	POLY 47

\$IBFTC	SCALE	LIST,REF,DECK	SCAL	1
C	SUBROUTINE	FUR SCALING LOGS OF STRESS	SCAL	2
C			SCAL	3
C	THE SCALED VALUES	LIE IN THE REGION -2 TO 2	SCAL	4
C			SCAL	5
	SUBROUTINE	SCALE	SCAL	6
C			SCAL	7
C	COMMON	/FDATA/OTHER1(600),X(200),XX(200),OTHER2(200)/N/N	SCAL	8
	BIG	= 0.	SCAL	9
	SMALL	= 1.E5	SCAL	10
	DO 10	K=1,N	SCAL	11
	BIG	= AMAX1(BIG,X(K))	SCAL	12
	SMALL	= AMIN1(SMALL,X(K))	SCAL	13
10		CONTINUE	SCAL	14
	A	= 4./(BIG-SMALL)	SCAL	15
	B=2.*	(BIG+SMALL)/(BIG-SMALL)	SCAL	16
	DO 20	K=1,N	SCAL	17
	XX(K)	= A*X(K)-B	SCAL	18
20		CONTINUE	SCAL	19
		RETURN	SCAL	20
		END	SCAL	21

REFERENCES

1. Larson, F. R.; and Miller, James: A Time-Temperature Relationship for Rupture and Creep Stress. Trans. ASME, vol. 74, no. 5, July 1952, pp. 765-771; Discussion, pp. 171-175.
2. Manson, S. S.; and Haferd, Angela M.: A Linear Time-Temperature Relation for Extrapolation of Creep and Stress-Rupture Data. NACA TN 2890, 1953.
3. Orr, Ramond L.; Sherby, Oleg D.; and Dorn, John E.: Correlations of Rupture Data for Metals at Elevated Temperatures. Trans. ASM, vol. 46, 1954, pp. 113-128.
4. Manson, S. S.: Design Considerations for Long Life at Elevated Temperatures. NASA TP 1-63, 1963.
5. Manson, S. S.; and Mendelson, A.: Optimization of Parametric Constants for Creep-Rupture Data by Means of Least Squares. NASA MEMO 3-10-59E, 1959.
6. Hamming, R. W.: Numerical Methods for Scientists and Engineers. McGraw-Hill Book Co., Inc., 1962, pp. 223-246.
7. Forsythe, G. E.: Generation and Use of Orthogonal Polynomials for Data-Fitting with a Digital Computer. J. Soc. Indust. Appl. Math., vol. 5, no. 2, June 1957, pp. 74-88.
8. Titran, Robert H.; and Hall, Robert W.: High-Temperature Creep Behavior of a Columbium Alloy, FS-85, NASA TN D-2885, 1965.
9. Murry, G.: Extrapolation of the Results of Creep Tests by Means of Parametric Formulae. Vol. 1 of Proc. Joint Int. Conf. on Creep, Inst. Mech. Eng., 1963, pp. 6-87 - 6-100.
10. Manson, S. S.; and Brown, W. F., Jr.: Time-Temperature-Stress Relations for the Correlation of Extrapolation of Stress-Rupture Data. Proc. ASTM, vol. 53, 1953, pp. 693-719.
11. Manson, S. S.; Succop, G.; and Brown, W. F., Jr.: The Application of Time-Temperature Parameters to Accelerated Creep-Rupture Testing. Trans. ASM, vol. 51, 1959, pp. 911-934.

TABLE I. - CALCULATION OF POLYNOMIALS FOR THEORETICAL DATA FOR THIRD DEGREE POLYNOMIAL

[Temperature intercept, T_a , 600° F.]

1	2	3	4	5	6	7	8	9	10	11	12
Index, i	Tempera- ture, T , $^{\circ}F$	Time, t, hr	Stress, σ , psi	log t	log σ	$\sigma^2(T-T_a)^2$	Scaled log σ , X	Polynomial			
								Q_1	Q_2	Q_3	Q_4
1	1100	4954.68	56 300	3.69501	4.75051	500	2.0	1	1.3619	-0.19594	-0.50845
2	1100	11365.9	19 800	4.05560	4.29666	500	1.3806	1	.30341	-1.6875	-.57205
3	1200	625.342	30 300	2.79612	4.48144	600	1.6328	1	.85576	-1.4583	1.7195
4	1200	2908.	5 080	3.46359	3.70586	600	.57433	1	-.80869	1.5741	-1.2980
5	1300	117.371	12 900	2.06956	4.11059	700	1.1267	1	.18925	2.5067	-1.0745
6	1300	1340.	778	3.12710	2.89098	700	-.53777	1	-2.2709	-.90880	.92564
7	1400	34.4856	4 190	1.53764	3.62221	800	.46017	1	2.8030	.015445	-.77354
8	1400	995.25	66	2.99793	1.81954	800	-2.0	1	.51879	-.78251	-.98133

TABLE II. - INTERMEDIATE CALCULATIONS FOR THEORETICAL

DATA FOR THIRD DEGREE POLYNOMIAL

[Temperature intercept, T_a , 600° F.]

1	2	3	4	5	6	7
Index, j	α	β	a	b	c	u
0	-----	-----	8.0	-----	.23.745	-----
1	0.27092	0.	5200.	3.48×10^6	14897.	-9.9146×10^{-3}
2	-.57813	1.6548	786.18	5.7589	2616.	-8.4266×10^{-4}
3	.28432	1.3315	465.68	7.6678	3796.9	-8.1771×10^{-5}
4	.41260	.80618	286.01	6.1816	2694.6	-3.6513×10^{-6}

TABLE III. - FIT FOR SEVERAL VALUES OF LINEAR
PARAMETER FOR THEORETICAL DATA

Degree of polynomial	Temperature, T_a	Variable, y_a	Deviation
2	500	10.54	0.008049
3	500	10.54	.009786
4	500	10.55	.010660
2	600	9.49	.004859
3	600	9.50	.000002
4	600	9.50	.000003
2	700	8.44	.015412
3	700	8.46	.013937
4	700	8.45	.014469

TABLE IV. - COMPOSITION OF STEELS RECEIVED
FROM GERMAN COOPERATIVE LONG-
TIME CREEP PROGRAM
[As-received, 20-mm-diam. bar stock.]

Element	Composition, percent		
	Steel		
	C (23b CK)	P (14a PA)	K (27b KK)
Carbon	0.065	0.270	0.068
Silicon	.47	.26	.45
Manganese	.60	.60	.73
Chromium	17.24	2.62	16.14
Molybdenum	2.08	.27	2.10
Columbium and tantalum	.02	Trace	.44
Nickel	11.90	.14	13.12
Titanium	.39	Trace	Trace
Vanadium	.10	.26	.05
Tungsten	Less than 0.005	Trace	Trace

TABLE V. - NASA RUPTURE DATA

(a) Steel K (27b KK)

Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr
1022.00	77 000.000	1.500	1600.00	20 000.000	0.400	a1112.00	60 000.000	12.900
a1022.00	72 500.000	13.800	1560.00	20 000.000	1.900	a1110.00	60 000.000	34.
a1022.00	72 000.000	10.	1520.00	20 000.000	4.450	a1080.00	60 000.000	52.200
a1022.00	70 000.000	36.700	a1480.00	20 000.000	23.700	a1080.00	60 000.000	37.400
a1022.00	68 000.000	60.400	a1460.00	20 000.000	25.500	a1050.00	60 000.000	239.
a1022.00	66 000.000	73.300	a1440.00	20 000.000	38.	a1030.00	60 000.000	445.
a1022.00	66 000.000	107.600	a1400.00	20 000.000	136.800	a1022.00	60 000.000	989.900
a1022.00	65 000.000	201.300	a1360.00	20 000.000	394.800	a1020.00	60 000.000	817.500
a1022.00	62 500.000	250.400	a1340.00	20 000.000	704.600	1040.00	75 000.000	.330
a1022.00	60 000.000	990.	a1320.00	20 000.000	1212.	1022.00	75 000.000	5.850
a1022.00	60 000.000	817.500	1320.00	40 000.000	2.700	a1000.00	75 000.000	15.600
a1022.00	55 000.000	3 680.	1290.00	40 000.000	7.500	a980.00	75 000.000	46.500
1112.00	68 000.000	.750	a1260.00	40 000.000	15.200	a960.00	75 000.000	138.
1112.00	65 000.000	2.250	a1230.00	40 000.000	44.400	a940.00	75 000.000	542.
1112.00	62 500.000	4.300	a1170.00	40 000.000	377.	a920.00	75 000.000	579.600
a1112.00	60 000.000	13.900	a1140.00	40 000.000	1417.	a1120.00	50 000.000	186.100
a1112.00	57 500.000	22.700	a1125.00	40 000.000	2110.	a1200.00	40 000.000	130.200
a1112.00	55 000.000	51.500	a1112.00	40 000.000	5367.	a1280.00	30 000.000	132.700
a1112.00	52 500.000	147.500	1200.00	60 000.000	.610	a1340.00	25 000.000	125.800
a1112.00	50 000.000	283.	1170.00	60 000.000	1.250	a1500.00	15 000.000	51.300
a1112.00	45 000.000	1 020.	1150.00	60 000.000	4.400	a1560.00	12 000.000	41.700
a1112.00	43 000.000	1 579.	1140.00	60 000.000	4.500	a1580.00	10 000.000	32.400
1112.00	37 000.000	13 140.	a1120.00	60 000.000	10.900	a1540.00	10 000.000	148.200

(b) Steel C (23b CK)

Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr
a1600.00	5 000.000	570.200	a1230.00	30 000.000	175.700	a1202.00	36 000.000	68.600
a1620.00	5 000.000	186.600	a1250.00	30 000.000	103.500	a1202.00	38 000.000	59.300
a1660.00	5 000.000	156.800	a1280.00	30 000.000	58.100	a1202.00	42 000.000	24.400
a1680.00	5 000.000	91.600	1292.00	30 000.000	21 300.	a1202.00	44 000.000	14.500
a1700.00	5 000.000	62.700	a1310.00	30 000.000	22.500	a1202.00	45 000.000	22.900
a1740.00	5 000.000	40.500	a1112.00	40 000.000	667.900	1202.00	46 000.000	7.
a1780.00	5 000.000	10.600	a1120.00	40 000.000	785.400	1202.00	48 000.000	2.850
a1425.00	10 000.000	1690.	a1150.00	40 000.000	266.700	1202.00	49 000.000	2.550
a1450.00	10 000.000	550.300	a1170.00	40 000.000	127.800	1202.00	50 000.000	1.470
a1480.00	10 000.000	270.	a1202.00	40 000.000	44.100	a1292.00	18 000.000	859.700
a1500.00	10 000.000	170.	a1202.00	40 000.000	74.	a1292.00	23 000.000	194.600
a1520.00	10 000.000	128.500	a1210.00	40 000.000	40.500	a1292.00	25 000.000	75.
a1560.00	10 000.000	40.	a1220.00	40 000.000	37.800	a1292.00	28 000.000	34.600
a1570.00	10 000.000	31.500	a1240.00	40 000.000	17.200	a1292.00	29 000.000	31.
a1600.00	10 000.000	15.800	1270.00	40 000.000	4.500	a1292.00	32 000.000	13.300
1650.00	10 000.000	5.250	1280.00	40 000.000	1.200	a1292.00	33 000.000	19.800
1700.00	10 000.000	1.750	1292.00	40 000.000	1.300	a1292.00	34 000.000	10.400
a1202.00	20 000.000	3307.	1300.00	40 000.000	.800	1292.00	36 000.000	2.750
a1260.00	20 000.000	667.400	a1112.00	34 000.000	2 274.	1292.00	37 000.000	7.600
a1290.00	20 000.000	255.	a1112.00	43 000.000	363.100	1292.00	38 000.000	1.650
a1292.00	20 000.000	347.100	a1112.00	46 000.000	233.900	a1060.00	60 000.000	42.500
a1292.00	20 000.000	363.	a1112.00	46 000.000	261.400	a1300.00	25 000.000	89.600
a1320.00	20 000.000	180.400	a1112.00	48 000.000	183.100	a1360.00	19 000.000	95.
a1360.00	20 000.000	82.	a1112.00	50 000.000	84.500	a1430.00	15 000.000	71.400
a1400.00	20 000.000	28.900	a1112.00	52 000.000	65.600	a1480.00	12 000.000	147.900
1440.00	20 000.000	9.	a1112.00	54 000.000	39.300	a1570.00	8 000.000	104.
1480.00	20 000.000	2.500	a1112.00	57 000.000	23.300	a1630.00	6 000.000	140.900
a1112.00	30 000.000	4258.	a1202.00	25 000.000	1 074.	a1140.00	34 000.000	1077.
a1160.00	30 000.000	1110.	a1202.00	34 000.000	199.400	a1320.00	15 000.000	1505.
a1180.00	30 000.000	696.300	a1202.00	35 000.000	124.300	a1480.00	8 000.000	2237.
a1202.00	30 000.000	350.				a1540.00	6 000.000	1258.

^aData point used in parametric analysis.

TABLE V. - Concluded. NASA RUPTURE DATA

(c) Steel P (14a PA)

Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr	Temperature, T, °F	Stress, σ, psi	Time, t, hr
932.00	65 000.000	3.800	a1250.00	10 000.000	19.200	a740.00	90 000.000	57.100
a932.00	60 000.000	14.150	a1220.00	10 000.000	42.	a785.00	80 000.000	84.
a932.00	60 000.000	14.400	a1180.00	10 000.000	167.	a820.00	70 000.000	195.800
a932.00	57 500.000	10.	a1170.00	10 000.000	203.400	a880.00	60 000.000	120.
a932.00	55 000.000	18.900	a1140.00	10 000.000	608.	a932.00	50 000.000	103.500
a932.00	52 500.000	51.	a1090.00	10 000.000	2639.	a1022.00	30 000.000	186.700
a932.00	40 000.000	623.	1100.00	40 000.000	1.300	a1050.00	25 000.000	123.500
a932.00	30 000.000	7 592.	1080.00	40 000.000	2.200	a1090.00	20 000.000	79.500
932.00	27 000.000	11 410.	1060.00	40 000.000	4.300	a1090.00	20 000.000	112.400
1022.00	58 000.000	.580	1050.00	40 000.000	6.800	a1120.00	16 000.000	183.500
1022.00	55 000.000	.717	1040.00	40 000.000	7.400	a1160.00	13 000.000	100.300
1022.00	50 000.000	1.280	a1020.00	40 000.000	22.500	a1230.00	8 000.000	97.900
1022.00	47 000.000	2.450	a1010.00	40 000.000	20.100	a1290.00	5 000.000	139.700
1022.00	47 000.000	6.200	a1000.00	40 000.000	63.300	a740.00	80 000.000	996.600
1022.00	45 000.000	3.500	a990.00	40 000.000	51.200	a780.00	70 000.000	1122.
1022.00	42 500.000	6.300	a980.00	40 000.000	80.600	a830.00	60 000.000	948.800
a1022.00	40 000.000	22.500	a960.00	40 000.000	192.100	a880.00	50 000.000	599.
a1022.00	37 500.000	12.	a940.00	40 000.000	427.900	a932.00	35 000.000	1902.
a1022.00	25 000.000	382.200	a930.00	40 000.000	623.	a980.00	30 000.000	754.800
1415.00	10 000.000	.170	a900.00	40 000.000	2572.	a1000.00	25 000.000	970.700
1340.00	10 000.000	1.500	932.00	70 000.000	1.400	a1030.00	20 000.000	1084.
1315.00	10 000.000	3.700	897.00	70 000.000	5.800	a1070.00	16 000.000	804.800
1290.00	10 000.000	6.100	a860.00	70 000.000	31.200	a1150.00	8 000.000	948.500
						a1220.00	5 000.000	960.

^aData point used in parametric analysis.

TABLE VI. - GERMAN RUPTURE DATA

Temperature, T , °F	Stress, σ , psi	Time, t , hr	Temperature, T , °F	Stress, σ , psi	Time, t , hr
Steel K (27b KK)			Steel C (23b CK)		
1022.00	76 899.999	0.100	1292.00	17 800.000	1 100.
1022.00	66 899.999	160.	1292.00	21 400.000	300.
1022.00	55 500.000	2 000.	1292.00	21 400.000	250.
1112.00	72 500.000	.100	1292.00	27 000.000	180.
1112.00	64 000.000	10.	1292.00	27 000.000	140.
1112.00	55 500.000	35.	1292.00	47 000.000	.100
1112.00	44 100.000	2 100.	Steel P (14a PA)		
1112.00	28 400.000	52 000.	932.00	84 000.000	0.100
Steel C (23b CK)			932.00	75 500.000	.100
1112.00	14 200.000	60 000.	932.00	78 399.999	2.
1112.00	17 800.000	30 000.	932.00	55 500.000	150.
1112.00	28 400.000	3 500.	932.00	44 100.000	1 700.
1112.00	28 400.000	3 000.	932.00	34 200.000	2 600.
1112.00	28 400.000	2 200.	932.00	27 000.000	16 000.
1112.00	35 600.000	1 200.	932.00	22 800.000	22 000.
1112.00	44 100.000	520.	932.00	17 100.000	100 000.
1112.00	51 200.000	150.	1022.00	72 599.999	.100
1112.00	59 800.000	.100	1022.00	69 699.999	.100
1202.00	11 400.000	82 790.	1022.00	65 500.000	1.200
1202.00	14 200.000	15 000.	1022.00	59 800.000	1.500
1202.00	17 800.000	6 500.	1022.00	35 600.000	150.
1202.00	22 800.000	1 800.	1022.00	27 000.000	300.
1202.00	28 400.000	550.	1022.00	22 800.000	400.
1202.00	35 600.000	124.	1022.00	22 800.000	900.
1202.00	42 700.000	5.	1022.00	17 100.000	2 100.
1202.00	52 600.000	.100	1022.00	13 900.000	6 500.
1292.00	11 400.000	30 000.	1022.00	13 900.000	8 000.
1292.00	11 400.000	20 000.	1022.00	11 100.000	10 000.
1292.00	13 900.000	4 500.	1022.00	8 830.000	68 000.

TABLE VII. - CREEP DATA FOR COLUMBIUM ALLOY FS-85

Temperature, T, °F	Stress, σ , psi	Time, t, hr		
		1-Percent creep	2-Percent creep	5-Percent creep
2005	25 000	0.6	3.0	6.1
1900	25 000	26.	33.	45.
1790	25 000	210.	257.	332.
2175	18 000	4.9	7.8	13.
2400	10 000	3.4	5.7	10.8
2300	10 000	25.4	41.	68.
2200	10 000	54.	84.	133.
2100	10 000	355.	500.	765.
2100	10 000	380	570.	875.
2000	10 000	775.	1325.	2175.
2000	10 000	900.	1420.	-----
2000	8 500	2480.	-----	-----
2575	6 000	5.6	10.	22.2
2200	6 000	425.	710.	1370.
2800	4 000	3.4	6.4	13.5
2620	4 000	14.4	26.	56.
2200	4 000	1140.	-----	-----
2900	3 000	2.6	5.4	13.8
3000	2 000	4.6	9.5	33.2
2450	2 000	-----	-----	950.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546